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THERMOELECTRIC COOLING: REVIEW AND APPLICATION

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December 1981

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Presented here are the theory, the applications, and an analysis of the problem of cooling a ground troop dressed in chemical warfare protective clothing. The analysis models the human thermal burden, resulting from metabolic and environmental heat production. For the thermal burdens considered, the analysis shows that the current thermoelectric cooling technology will not practically or efficiently support total thermal regulation. A discussion of marginal cooling is recommended as a possible option if thermoelectric cooling is to be pursued.

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THERMOELECTRIC COOLING:
REVIEW AND ANALYSIS

INTRODUCTION

Why consider thermoelectric cooling as a means of dissipating the heat generated by the environment and human metabolism for a ground troop dressed in chemical warfare (CW) protective clothing? This Review attempts to answer this question and also to explain some of the advantages and disadvantages associated with thermoelectric cooling technology.

COMPARISON OF COOLING TECHNOLOGIES

Since thermoelectric cooling systems (heat pumps) are often compared to conventional electromechanical cooling systems, one way to highlight the similarities and differences in these two refrigeration technologies is to describe the respective systems.

Conventional Electromechanical Cooling Technology

In a conventional electromechanical cooling system, mechanical work is performed on a fluid; and the result is a thermodynamic cycle (1-5). During part of the cycle, the temperature of the fluid is above the ambient sink temperature, and thus dissipates heat. During another portion of the cycle, the temperature of the fluid is below the temperature of the medium to be cooled, and thus absorbs heat. A conventional electromechanical cooling system (Fig. 1) has four fundamental components: a condenser, compressor, evaporator, and an expansion valve (1,2,5). As illustrated in Figure 1, beginning at point 1, the fluid is usually in the gaseous state (mixture of vapor and liquid droplets or mist). The compressor raises the pressure and temperature of the fluid. The compression must be sufficient to raise the temperature of the vapor (point 2) above that of the ambient sink. The condenser is a heat exchanger which cools the vapor by dissipating its superheat and latent heat of condensation to the ambient, and the result is a subcooled liquid (point 3). The expansion valve is a device to separate regions of high and low pressure. Expansion through the valve results in a drop in the fluid temperature below that of the source of heat (point 4). The evaporator is a heat exchanger which absorbs heat from the medium to be cooled, and thus raises the temperature of the fluid to point 1 (Fig. 1), from which the thermodynamic cycle originated.

EDITOR'S NOTE: Available at the close of this publication is a selective list (plus definitions) of the "Abbreviations, Acronyms, and Symbols" used throughout the Review.

Thermoelectric Heat Pump

In contrast to the conventional electromechanical cooling system, a thermoelectric heat pump is a solid-state device with no moving parts, fluids, or gases. The basis of this system (heat pump) is the thermoelectric element. As illustrated in Figure 2, a thermoelectric element consists of a series connection of two semiconductors, one of which possesses electron conductivity (n-type), and the other, hole conductivity (p-type) (6-46). With a suitable source of direct current input power, a thermoelectric element forms a hot and cold junction with the two semiconductor materials. At the cold junction, energy, in the form of heat, is absorbed by electrons as they pass from a low energy level to a higher energy level. At the hot junction, on the other hand, heat is liberated because the electrons return from the high energy level to the lower energy level (6,72).

Thermoelectric heat pumps were originally developed in the 1960's to satisfy unique and exacting military and aerospace temperature regulation applications (73-86). When these devices failed to compete economically with conventional electromechanical cooling technologies for mass applications (such as domestic refrigerators), most large companies, and industry in general, lost interest. Since then, these devices have found use primarily in special-purpose applications (7-10,11-13,16,21,22,24-27,29,30,33-35,38,40-42,54,56,58, 68,69,71,73-253) that include:

a. military/aerospace (cooling infrared, photomultiplier, and charge-coupled-device detectors);
b. laboratory/scientific (laser tuning, cooling electronic integrated circuits, cold chambers, microtome stage coolers, osmometers, and dew-point hygrometers);
c. medical (hypothermia blanket chillers, ophthalmological cornea freezers, blood analyzers, and tissue processing refrigerators); and
d. commercial (aircraft water coolers, mobile refrigerators, restaurant display case coolers).

Thermoelectric heat pumps, commercially available in various shapes and sizes, provide a means to cool objects, fluids, and gases to well below ambient temperatures. A typical thermoelectric module (fundamental building block) consists of 44 thermoelectric semiconductor elements; is 1.5 in. by 1.5 in. square, and 0.25 in. thick (3.81 cm by 3.81 cm square by 0.64 cm thick); and weighs approximately 25 grams (254-257).

In addition to being compact, lightweight, and insensitive to orientation, thermoelectric heat pumps offer very high reliability, good maintainability, low cost of operation, accurate and rapid thermal regulation, and a low operating noise level. The high reliability of thermoelectric heat pumps has been demonstrated by a number of operating systems which have performed for very long periods of time with no thermoelectric module failures or known degradations (113,122,143,145,149,150,159,179,217,233,234,236,246). The solid-state modular nature of the thermoelectric heat pump module permits rapid replacement of defective components and prompt reentry into service. In contrast to operators of conventional compressor refrigeration systems, service personnel do not require high skill levels (and thus need shorter training periods).

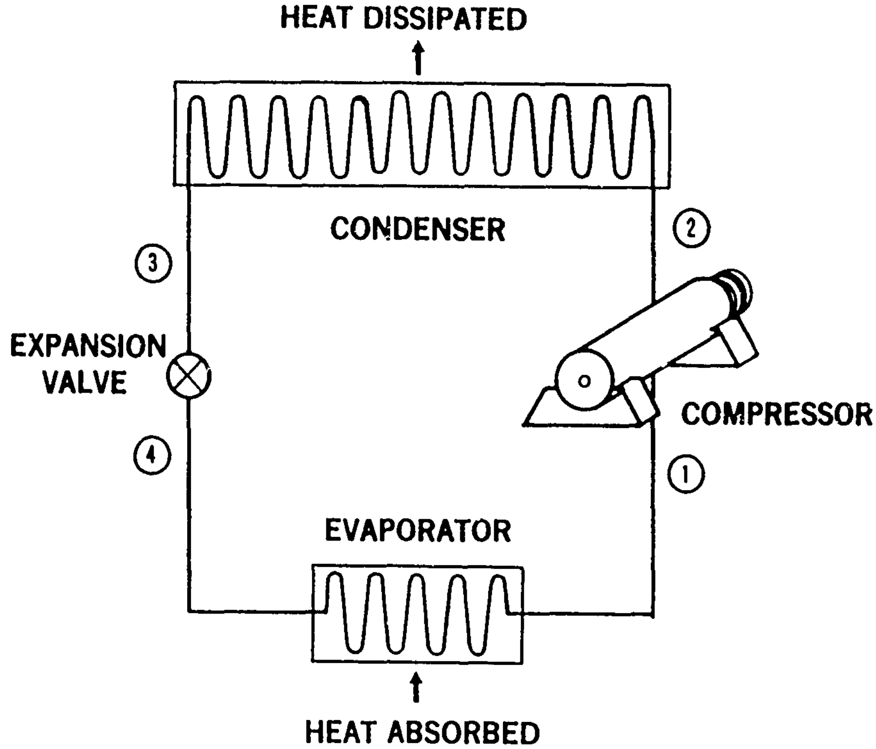


Figure 1. Typical conventional electromechanical cooling system.

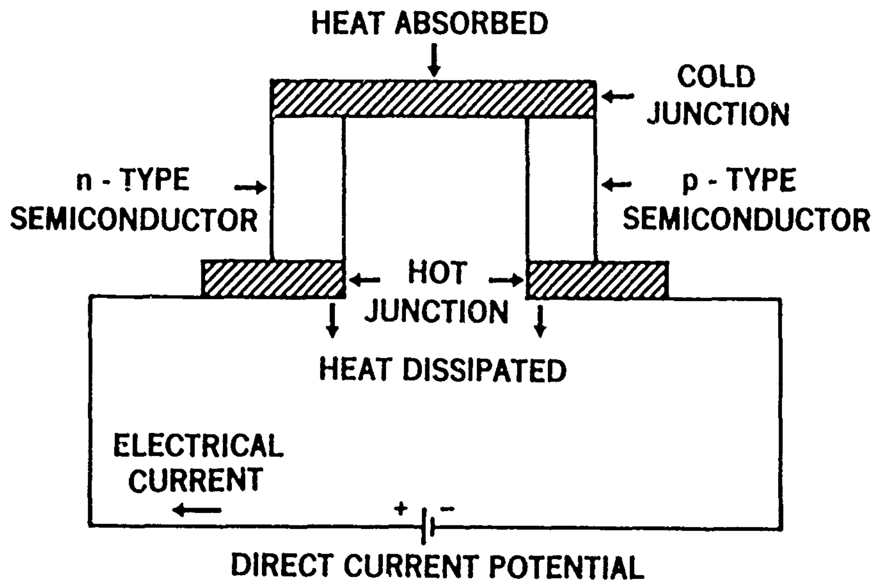


Figure 2. Typical thermoelectric element cooling system.

Comparison of Conventional Electromechanical Cooling and Thermoelectric Heat Pump Technologies

A comparison between conventional electromechanical cooling technology and thermoelectric heat pump systems was addressed at the Tenth International Congress on Cooling, held at Kodani, and the results have been reported in the literature (32,68,117).

The basis of conventional electromechanical cooling is the cooling medium (fluid), and its efficiency can be compared with that of the thermoelectric semiconductor material. Compression and expansion of the conventional electromechanical cooling medium in a thermodynamic cycle corresponds to the exchange of heat between a thermoelectric semiconductor element and the ambient. The mechanical losses that occur during a conventional electromechanical cooling medium's compression and expansion can be compared to the degradation of the thermoelectric semiconductor material's figure of merit (Z), which is a function of the material's junction contact resistances and dependency on temperature. Finally, the performance of a compressor in a conventional cooling system can be compared to the performance of the direct current power supply of the thermoelectric heat pump. The efficiency of each process or element (η_1 through η_4) is summarized in Table 1 (32,68,117):

TABLE 1. COMPARISON OF CONVENTIONAL ELECTROMECHANICAL COOLING AND THERMOELECTRIC HEAT PUMP TECHNOLOGIES

Technology	Efficiency η_1	η_2	η_3	η_4
Conventional	0.8 (cooling medium)	0.5 (compression/ expansion)	0.5 (mechanical losses)	0.6 (compressor)
Thermoelectric	0.1 (material)	0.9 (heat exchange)	0.7 (contact resistance)	0.7 (power supply)

If a thermoelectric heat pump were to have an identical overall performance efficiency representative of the present conventional electromechanical cooling system technology, the thermoelectric semiconductor material's figure of merit (Z) would have to increase from the current average value of 3×10^{-3} °K^{-1} to approximately 10×10^{-3} °K^{-1} (32,68,117). On the basis of present knowledge, the estimated value of Z for any material will not exceed 6×10^{-3} °K^{-1} (258-265).

Thus, to a considerable extent, the inherent capabilities and limitations of thermoelectric heat pumps are determined by the characteristics of the thermoelectric semiconductor material and fabrication process. Factors--such as temperature limitations, operating efficiency, reliability, durability, size, weight, configuration, power requirements, and cost--are all related to the fundamental thermoelectric semiconductor material and fabrication process. To provide a basis for evaluating the feasibility of using thermoelectric heat pump modules to dissipate the heat generated by the environment and human metabolism for a ground troop dressed in CW protective clothing, the important characteristics of thermoelectric materials are summarized here.

THERMOELECTRIC MATERIALS

Solid-state materials are generally classified by their electrical properties (metals, semiconductors, and insulators). The useful crystalline materials for thermoelectric elements are classified as semiconductors, having an electrical conductivity between metals and insulators. With respect to thermoelectric materials, the most important material characteristic--the figure of merit (Z)--describes the usefulness of a material by the following relationship (49-53,61,63-65,265-279):

$$Z = \frac{\alpha^2 \delta}{k} \tag{1}$$

where α = Seebeck coefficient

δ = electrical conductivity

k = thermal conductivity

As shown by Equation (1), control of the Seebeck coefficient, electrical conductivity, and thermal conductivity is essential to obtain a high figure of merit. In addition, all three quantities are a function of the density of free charge carriers (N_c) in the material (265-279).

Several investigators have shown that a semiconductor's figure of merit (Z) has a maximum value in the region where the free charge carrier density (N_c) is on the order of 10^{18} to 10^{21} carriers per cubic centimeter (265-279). The relationship of the three important thermoelectric material properties (α, δ, and k), as a function of the free charge carrier concentration (N_c), is shown in Figure 3 (277-293). The electrical conductivity (δ) increases with increasing carrier concentration (277,278,280-286). The thermal conductivity (k) has two components: a lattice thermal conductivity which is independent of the carrier concentration; and the electronic thermal conductivity which is proportional to the free charge carrier concentration (277-279,282-293). Thus, the difficulty in identifying an optimum thermoelectric material is now apparent. Insulators have large α's, but low electrical conductivities. Metals, on the other hand, have very small α's. The most favorable figure merit value corresponds to those α's, δ's, and k's characteristic of highly doped, near-degenerate semiconductors (semi-metals) (277-282,287-293).

In the selection of a thermoelectric semiconductor material, a large free charge carrier concentration (N_c) is desirable--one which, from a solid-state physics viewpoint, is associated with a low band-gap energy (E_g)

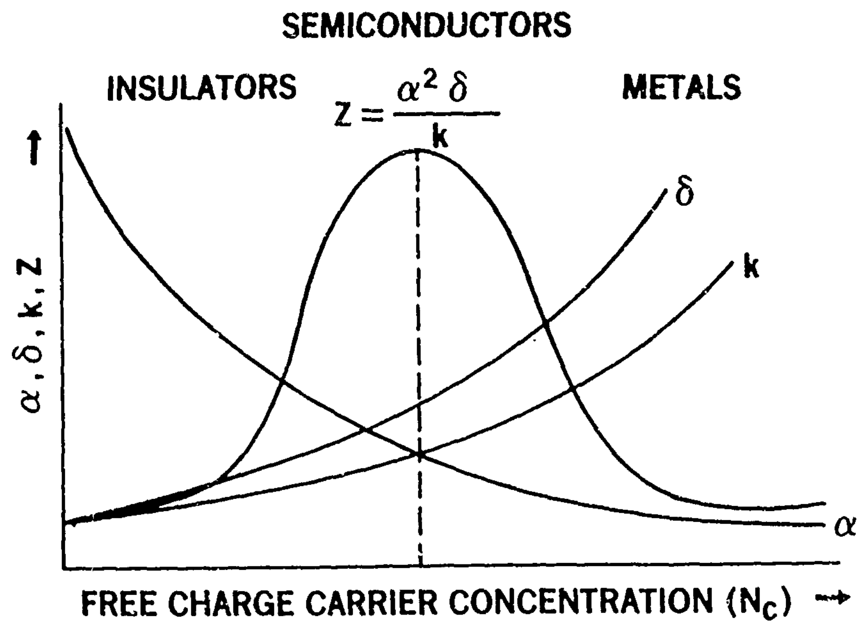


Figure 3. Thermoelectric material properties as a function of the free charge carrier concentration.

(292,293). Maximizing the band-gap energy is important, however, to avoid intrinsic conduction at the highest anticipated operating temperature. Extensive research has led to the discovery of several thermoelectric semiconductor materials. The common thermoelectric materials and their important physical properties are summarized in Table 2 (6,7,10,12,16,19,20,27,28,31,35,36,45, 49-52,54,55,59-63,66,67,73,74,81,114,116,118,119,254-256,277,280-286,288,289, 294-372).

For applications near ambient temperature (300°K), Bi_2Te_3, $BiSb_4Te_{7.5}$, and Bi_2Te_2Se are the best semiconductor materials for thermoelectric heat pump applications (295,299-302,305-309,313,314,316,334,342,346,357,363,368). Improvement in the techniques of solid solution alloying of $BiSb_4Te_{7.5}$ (p-type semiconductor) and Bi_2Te_2Se (n-type semiconductor) has been the principal factor that has advanced the state of the art for thermoelectric heat pump materials.

THEROMELECTRIC DEVICE PERFORMANCE AND THEORY

The thermoelectric phenomenon is the result of five distinct effects (Seebeck, Peltier, Thomson, Fourier, and Joule) that act concurrently (3,7, 8-16,24,27,31,40,45,49,57,62,68). The Seebeck, Peltier, and Thomson effects account for the reversible interchange of electrical and thermal energies. The Fourier and Joule effects account for the irreversible effects of heat evolution. A rigorous description of this subject is available in the literature (8-16). A summary of the important analytical relationships is presented, however, so that the problem of cooling a ground troop dressed in CW protective clothing can be evaluated on a quantitative basis.

A thermoelectric couple is an electrical circuit consisting of two different semiconductors connected in series (Fig. 4, Views a and b). The two semiconductors are n-type and p-type. An n-type semiconductor has an excess of electrons and is classified as having negative thermoelectric power. A p-type semiconductor has a deficiency of electrons (an excess of holes) and is classified as having positive thermoelectric power (3,7,8-16,27,68).

TABLE 2. KNOWN THERMOELECTRIC MATERIALS

Materials	Figure of merit (Z) (°K^{-1})	Lattice thermal conductivity (W•cm^{-1}•°K^{-1})	Electronic thermal conductivity (W•cm^{-1}•°K^{-1})	Semiconductor type	Operating temperature (°K)
Bi_2Te_3	2×10^{-3}	0.016	0.004	n or p	300
$BiSb_4Te_{7.5}$	3.3×10^{-3}	0.010	0.004	p	300
Bi_2Te_2Se	2.3×10^{-3}	0.013	0.003	n	300
PbTe	1.2×10^{-3}	0.02	0.003	n or p	300
Pb_2TeSe	1.3×10^{-3}	0.015	0.003	n	700
GeTe(+Bi)	1.6×10^{-3}	0.02	-----	p	800
ZnSb	1.2×10^{-3}	0.17	-----	p	500
$AgSbTe_2$	1.8×10^{-3}	0.006	0.002	p	700
MnTe	4×10^{-4}	0.013	-----	p	1000
InAs(+P)	6×10^{-4}	0.07	-----	n	900
CeS	4×10^{-4}	0.01	-----	n	1200
CeS(+Ba)	8×10^{-4}	0.01	-----	n	1200
ZnO	---------	----	-----	n	1500
Cu_2S	---------	----	-----	p	----
Cu_8Te_3	1.5×10^{-2}	0.012	-----	-------	1100
InTe	5×10^{-4}	-----	0.008	p	700
Ge-Si	9×10^{-4}	-----	0.033	n	1200
Ge-Si	6×10^{-4}	-----	0.033	p	1200

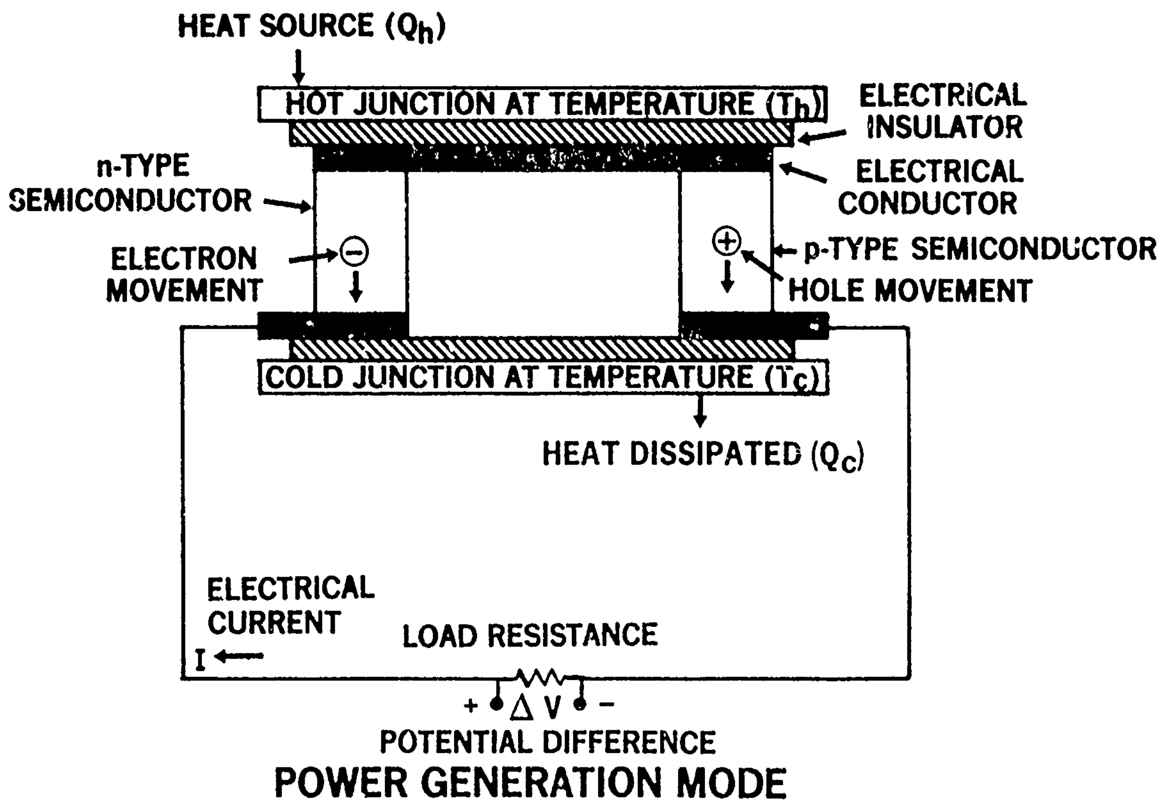
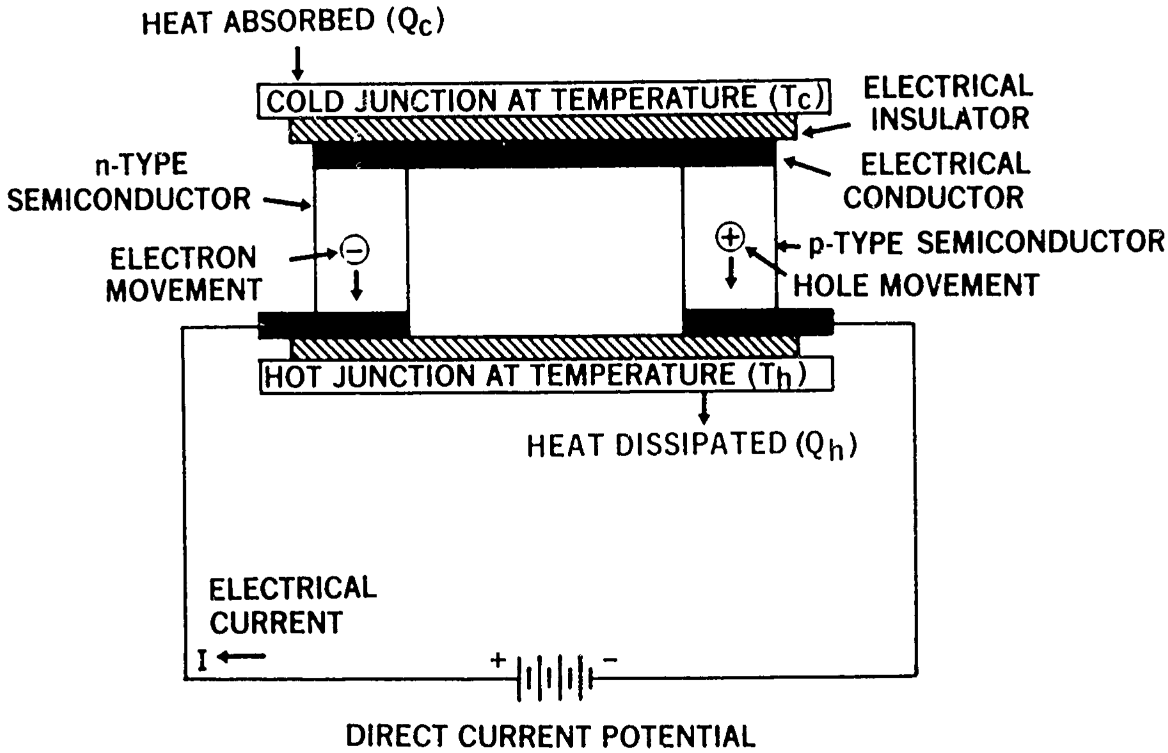


Figure 4: View a. Thermoelectric device operation: Power generation mode.



HEAT PUMP MODE

Figure 4: <u>View b</u>. Thermoelectric device operation: Heat pump mode.

Seebeck Effect

Thermoelectric power generation is the result of the Seebeck effect (8-16,373,374). As shown in Figure 4, View a (power generation mode), when the two dissimilar semiconductor junctions are maintained at different temperatures (T_c and T_h), a potential difference (ΔV) is created and results in a current flow (I). This open circuit potential difference can be expressed (8-16,373,374) as:

$$\Delta V = \alpha(T)[T_h - T_c] \tag{2}$$

in which $\alpha(T)$, the Seebeck coefficient of the two semiconductors, is given by:

$$\alpha(T) = \alpha_{p\text{-type}} - \alpha_{n\text{-type}} \tag{3}$$

Peltier Effect

Thermoelectric heat pumping, the principal phenomenon of interest in this Review, utilizes a reverse scheme known as the Peltier effect. In 1834, Jean C. A. Peltier discovered that the passage of an electrical current through the junction of two dissimilar conductors could either cool or heat a junction depending on the direction of the current (8-16,375-378). In addition, the heat generation or absorption rates (Q_c and Q_h) were proportional to the magnitude of the current and dependent on the temperature of the junction. In Figure 4, View b (heat pump mode), an electrical current (I) passes from the n-type semiconductor to the p-type semiconductor. The temperature of the cold junction (T_c) decreases, and heat is absorbed from the ambient. The heat absorption (cooling) occurs because electrons pass from a low energy level in the p-type semiconductor to a higher energy level in the n-type semiconductor. The absorbed heat is conducted through the semiconductor materials to the hot junction (T_h) by electron transport. The heat is then dissipated as the electrons return to a lower energy level in the p-type semiconductor. The quantity of heat absorbed (Peltier heat) at the thermoelectric junction is given by (8-16,375-378):

$$Q_p = \alpha(T)TI \tag{4}$$

where $\alpha(T)$ is the Seebeck coefficient of the two materials, T is the absolute temperature of the junction, and I is the current flowing through the junction.

Thomson Effect

As shown in Figure 5, the Thomson effect (differential Peltier effect) results in heating or cooling in a homogeneous material when an electrical current flows in the direction of a temperature gradient (3,7,8-16).

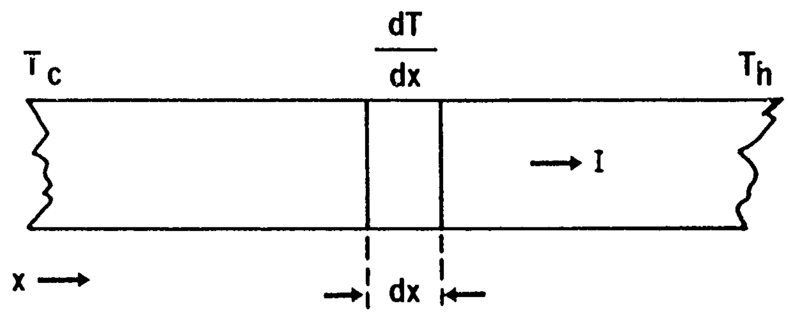


Figure 5. Thomson effect.

The Thomson heat per unit length of a material is given by (8-16):

$$Q_T = \tau(T) I \frac{dT}{dx} \tag{5}$$

for

$$\tau(T) = T \frac{d\alpha(T)}{dT} \tag{6}$$

where $\tau(T)$ is the Thomson coefficient of the material; I is the current flowing through the material; T is the absolute temperature; $\alpha(T)$ is the Seebeck coefficient of the material; and x is the position along the material in the direction of the current flow (I). If Q_T is the heat absorbed when the directions of I and $\frac{dT}{dx}$ coincide, then $\tau(T)$ is positive. If Q_T is the heat dissipated when the directions of I and $\frac{dT}{dx}$ coincide, then $\tau(T)$ is negative. In addition, it is obvious from Equation (6) that if the Seebeck coefficient [$\alpha(T)$] is independent of temperature, or a very weak function of temperature, the Thomson coefficient [$\tau(T)$] is zero or very nearly zero.

Fourier Effect

The Fourier effect (thermal conduction) of a material is due to the fact that a temperature gradient in a material induces a flow of heat in the direction of the negative temperature gradient (3,7,8-16). The rate at which heat is conducted across a unit surface of a material can be expressed (3,7,8-16) as:

$$Q_F = - k(T) \frac{dT}{dx} \tag{7}$$

for

$$k(T) = \left(\frac{k^*(T)_{p\text{-type}} A_{p\text{-type}}}{\ell_{p\text{-type}}}\right) + \left(\frac{k^*_{n\text{-type}} A_{n\text{-type}}}{\ell_{n\text{-type}}}\right) \tag{8}$$

where k(T) is the net thermal conductivity of the materials; T is the absolute temperature; x is the position along the material in the direction of the flow of heat; A is the cross-sectional area of a material; ℓ is the length of a material; and k*(T) is the thermal conductivity of a material.

Joule Effect

Finally, the Joule effect occurs when a current flows through the resistance of an isothermal conductor. Joule heat is given by (3,7,8-16,24,40,45):

$$Q_J = I^2 R(T) \tag{9}$$

for

$$R(T) = \left(\frac{\rho(T)^*_{p\text{-type}} \ell_{p\text{-type}}}{A_{p\text{-type}}}\right) + \left(\frac{\rho(T)^*_{n\text{-type}} \ell_{n\text{-type}}}{A_{n\text{-type}}}\right) \tag{10}$$

where I is the current flowing through the materials; R(T) is the net electrical resistance of the materials; $\rho^*(T)$ is the resistivity of a material; ℓ is the length of a material; and A is the cross-sectional area of a material.

Thermodynamic Analysis

Thermodynamic analysis of a thermoelectric heat pump requires a relationship between the net heat absorbed at the cold junction and the net heat dissipated at the hot junction. The total heat flow across a thermoelectric junction is the sum of the heat flows due to Peltier heat (Q_P), Thomson heat

(Q_T), Fourier heat (Q_F), and Joule heat (Q_J). A heat balance equation for the cold junction in Figure 4 is:

$$Q_c = Q_P + Q_T - Q_F - Q_J \tag{11}$$

Similarly, a heat balance equation for the hot junction in Figure 4 is:

$$Q_h = Q_P - Q_T - Q_F + Q_J \tag{12}$$

Several practical and realistic assumptions are used to simplify the complex thermodynamic calculations (3,7,8-16,24,27,31,40,45,68):

a. Heat transfer between the hot and cold junctions to the ambient is perfect.
b. Thermal insulation in the thermoelectric device is perfect.
c. The thermoelectric device's junction resistance is negligible compared to the bulk resistance of the semiconductor material.
d. The electrical conductivity (δ), thermal conductivity (k), and Seebeck coefficient (α) of the semiconductor materials are independent of temperature.

With these assumptions, Equations (11) and (12) reduce to:

$$Q_c = Q_P - Q_F - Q_J \tag{13}$$

and

$$Q_h = Q_P - Q_F + Q_J \tag{14}$$

The Thomson heat (Q_T), given by Equation (5), is zero because of Equation (6) and the assumption that the Seebeck coefficient [$\alpha(T)$] is independent of temperature. Substitution of the more complex expressions for Q_P, Q_F, and Q_J yields:

$$Q_c = \alpha T_c I - k\Delta T - 1/2\ I^2R \tag{15}$$

$$Q_h = \alpha T_h I - k\Delta T + 1/2\ I^2R \tag{16}$$

Thermoelectric heat pumps may be designed from two approaches: maximize the coefficient of performance (Φ_{max}); or, maximize the heat pumping rate (Q_c max) (3,7,8-16,24,27,31,40,379). As will be shown, both of these parameters depend strongly on the operating temperature of the heat pump.

The coefficient of performance (Φ) is given by the ratio of the rate of heat removal from the cooled junction (Q_c) divided by the electrical input power (P) (7,8-16,31,379):

$$\Phi = \frac{Q_c}{P} \tag{17}$$

The heat pumping rate (Q_c) (refrigeration or cooling effect) is the rate at which heat is removed from the cold reservoir.

Maximum Coefficient of Performance

The rate of heat removal from the cold reservoir is given by Equation (15). From Figure 4 (heat pump mode), the applied voltage is:

$$V = \alpha\Delta T + IR \tag{18}$$

where

$$\Delta T = T_h - T_c \tag{19}$$

and the input power is:

$$P = VI \tag{20}$$

and from Equation (18):

$$P = \alpha . \Delta T + I^2R \tag{21}$$

or

$$P = \frac{V(V-\alpha\Delta T)}{R} \tag{22}$$

if Equations (20) and (21) are solved for I.

From Equations (15), (17), and (21), the coefficient of performance for the thermoelectric heat pump is:

$$\Phi = \frac{(\alpha T_c I - 1/2\ I^2 R - k\Delta T)}{(\alpha I \Delta T + I^2 R)} \tag{23}$$

If a new variable is defined such that

$$m = \frac{IR}{\alpha} \tag{24}$$

and Equation (24) is substituted into Equation (23), the coefficient of performance can be written as:

$$\Phi = \frac{[mT_C - 1/2\ m^2 - k\Delta T]}{(\alpha I \Delta T + I^2 R)} \tag{25}$$

The product of the thermal conductance and series resistance of the thermoelectric heat pump is, from Equations (8) and (10):

$$KR = k_{n\text{-type}}\rho_{n\text{-type}} + k_{n\text{-type}}\rho_{p\text{-type}}\left(\frac{A_{n\text{-type}}\ell_{p\text{-type}}}{A_{p\text{-type}}\ell_{n\text{-type}}}\right) +$$

$$k_{p\text{-type}}\rho_{n\text{-type}}\left(\frac{A_{p\text{-type}}\ell_{n\text{-type}}}{A_{n\text{-type}}\ell_{p\text{-type}}}\right) + k_{p\text{-type}}\rho_{p\text{-type}} \tag{26}$$

Equation (26) can be simplified by making the following substitutions:

$$k_{n\text{-type}} = k_n$$

$$k_{p\text{-type}} = k_p$$

$$\rho_{n\text{-type}} = \rho_n$$

$$\rho_{p\text{-type}} = \rho_p$$

$$\frac{A_{n\text{-type}}}{\ell_{n\text{-type}}} = \nu_n$$

$$\frac{A_{p\text{-type}}}{\ell_{p\text{-type}}} = \nu_p$$

Thus,

$$KR = k_n\rho_n + k_n\rho_p\left(\frac{\nu_n}{\nu_p}\right) + k_p\rho_n\left(\frac{\nu_p}{\nu_n}\right) + k_p\rho_p \tag{28}$$

Examination of Equations (25) and (28) reveals two variables which can be adjusted to maximize the coefficient of performance. These are the parameters m and the shape ratio $\left(\frac{\nu_n}{\nu_p}\right)$.

From a physical viewpoint of the purpose of a heat pump, the coefficient of performance is a positive quantity [Eq. (17)]; and the coefficient is maximized by minimizing the product KR. The value of $\left(\frac{\nu_n}{\nu_p}\right)$--which maximizes the coefficient--can be obtained by setting the partial derivative of KR with respect to $\left(\frac{\nu_n}{\nu_p}\right)$ equal to zero. The result is:

$$\left(\frac{\nu_n}{\nu_p}\right) = \left(\frac{\rho_n k_p}{\rho_p k_n}\right)^{1/2} \tag{29}$$

and the value of KR when $\left(\frac{\nu_n}{\nu_p}\right)$ has this value is:

$$KR_{min} = \left[(\rho_n k_n)^{1/2} + (\rho_p k_p)^{1/2}\right]^2 \tag{30}$$

The value of the coefficient of performance of the heat pump with this optimum geometry is:

$$\phi = \frac{\left[mT_c - 1/2\ m^2 - \left(\frac{\Delta T}{Z}\right)\right]}{(m\Delta T + m^2)} \tag{31}$$

where the figure of merit (Z) is:

$$Z = \left\{\frac{\alpha}{[(\rho_n k_n)^{1/2} + (\rho_p k_p)^{1/2}]}\right\}^2 \tag{32}$$

The current which maximizes the coefficient of performance is found by setting the derivative of the coefficient of performance with respect to m equal to zero. The value obtained is:

$$I = \frac{\alpha \Delta T}{[R(\omega-1)]} \tag{33}$$

where

$$\omega = (1+Z\overline{T})^{1/2} \tag{34}$$

and

$$\overline{T} = 1/2(T_h+T_c) \tag{35}$$

At this value of current, the coefficient of performance of the heat pump is:

$$\phi_{max} = \left(\frac{T_c}{\Delta T}\right) \left\{\frac{[\omega-(\frac{T_h}{T_c})]}{(\omega+1)}\right\} \tag{36}$$

Thus, Equation (36) shows that the maximum coefficient of performance depends on the properties of the thermoelectric materials only through the figure of merit (Z). From Equations (18) and (33), the value of the applied voltage which maximizes the coefficient of performance is:

$$V = \frac{(\alpha \Delta T \omega)}{(\omega-1)} \tag{37}$$

Another significant fact is that the applied voltage is independent of the geometry of the thermoelectric heat pump. The power input, from Equation (22) is:

$$P = \left(\frac{\omega}{R}\right)\left[\frac{(\alpha\Delta T)}{(\omega-1)}\right]^2 \tag{38}$$

For completeness, the heat pumping rate with maximized coefficient of performance can be calculated using Equations (17), (36), and (38). However, the series resistance value of R must first be calculated for Equation (38). The shape ratio $\left(\frac{\nu_n}{\nu_p}\right)$, given by Equation (29), maximizes the coefficient of performance. The series resistance, defined by Equation (8), becomes:

$$R = \left(\frac{\alpha}{Z^{1/2}}\right)\left(\frac{1}{\nu_p}\right)\left(\frac{\rho_p}{k_p}\right)^{1/2} = \left(\frac{\alpha}{Z^{1/2}}\right)\left(\frac{1}{\nu_n}\right)\left(\frac{\rho_n}{k_n}\right)^{1/2} \tag{39}$$

Thus, the pumping rate is:

$$Q_c = \left(\frac{T_c}{\Delta T}\right)\left\{\frac{\left[\omega-\left(\frac{T_h}{T_c}\right)\right]}{(\omega+1)}\right\}\left[\left(\frac{\omega\nu_p Z^{1/2}}{\alpha}\right)\left(\frac{k_p}{\rho_p}\right)^{1/2}\right] \tag{40}$$

Maximum Heat Pumping Rate

The current for a maximum heat pumping rate can be obtained by taking the derivative of the heat pumping rate equation [Equation (15)] with respect to the current (I), and setting the result equal to zero. The current which maximizes the heat pumping rate is:

$$I = \frac{\alpha T_c}{R} \tag{41}$$

and the applied voltage, using Equation (18), is:

$$V = \alpha T_h \tag{42}$$

Thus, the maximum heat pumping rate at the current given by Equation (41) is:

$$Q_{c\ max} = \left(\frac{\alpha^2 T_c^{\ 2}}{2R}\right) - k\Delta T \tag{43}$$

In addition, as evident from Equation (43), the maximum temperature difference which a thermoelectric heat pump can produce (setting the derivative of $Q_{c\ max}$ with respect to I equal to zero) is:

$$\Delta T = \frac{\alpha^2 T_c^{\ 2}}{2RK} \tag{44}$$

Furthermore, ΔT can be maximized by minimizing KR. From Equations (30) and (32), ΔT_{max} is given by:

$$\Delta T_{max} = \frac{1}{2} Z T_c^{\ 2} \tag{45}$$

Fundamental Thermoelectric Heat Pump Design Philosophy

The design of a thermoelectric heat pump for a given application will probably be constrained with several boundary conditions. Representative of typical boundary conditions are: the magnitude of the heat load to be pumped; the temperature difference between the source and sink; the thermoelectric properties of the semiconductor materials; the contact resistivity of the thermoelectric element; the volume and space available; and the desirable economic features to be incorporated into the design. Even though a near complete set of boundary conditions might be available, the design of a thermoelectric heat pump is not completely straightforward. Many design problems stem from economic rather than technical considerations. The example in the following section emphasizes this point.

DESIGNING WITH THERMOELECTRIC HEAT PUMP TECHNOLOGY

Fundamentals to be Considered

A thermoelectric heat pump can be operated under two basic conditions (3,7,8-16,24,27,31,40,379):

a. the condition of maximum coefficient of performance (Φ_{max}), and
b. the condition of maximum heat pump capacity ($Q_{c\ max}$).

In the first case, the maximization of the coefficient of performance minimizes the electrical input power required to dissipate a given quantity of heat per unit of time, but maximizes the total number of thermoelectric heat pump elements needed for the system. In the second case, the maximization of the heat pump capacity maximizes the quantity of heat dissipated per unit of time, but at the expense of the electrical input power required to operate the system.

In the example design that follows, calculations are made for the two basic conditions. For a final design, the designer would optimize a hardware configuration somewhere between the two alternatives in order to accommodate such physical constraints as weight, volume, power supply requirements, and cost. The solution to this tedious problem, however, can conveniently be obtained using an iterative computerized technique--such as the Martin Marietta Thermal Analyzer System (MITAS)--that uses a lumped-parameter thermal network analysis method (380-381).

Statement of the Problem

As a result of the metabolic and environmental heat burden placed on a ground troop wearing CW protective clothing, a thermal conditioning system is needed to extend the time an individual can comfortably work in this environment. A possible technology for the thermal conditioning system is a thermoelectric heat pump. The potential for thermoelectric heat pumping is analyzed by modeling the human thermal conditioning problem (Fig. 6), as follows:

The design can be attacked in three phases. First, a certain amount of heat must flow from the reservoir (heat source) to the cold sink of the thermoelectric heat pump. Next, that same heat loa[illegible]s an additional amount must be pumped through the module from the cold sink to the hot sink. In the last phase, heat must flow from the hot sink to some external reservoir (the ambient). The first and last phases require the application of heat-transfer laws, while the second phase requires use of the analytical thermoelectric principles presented in this Review.

As shown in Figure 6, an individual dissipates a known quantity of heat (Q_m) that is dependent on the metabolic rate. For this analysis, the metabolic rates and their associated average heat loads are summarized in Table 3 (382). Since the subject is dressed in CW protective clothing, stabilizing the individual's temperature (oral) (T_i) at a nominal 98.6°F (37°C) is desirable. Having the temperature of the air inside the protective clothing (T_s) equal to the temperature of the thermoelectric cold sink (T_c = 74°F or 23.3°C) is also desirable. The ambient temperature (T_a), external to the protective clothing, is 90°F (32.2°C) for this analysis (a realistic and typical value). The temperature of the heat sink (T_h) is 105°F (40.6°C) to optimize the thermoelectric heat pump performance and heat transfer to the ambient. The environmental heat load (Q_e) gained by a ground troop dressed in CW protective clothing is primarily the result of the radiant energy from the sun and sky, both that which is direct and that which is reflected and reradiated by the terrain. Adolph reports that, for an individual at rest, approximately 95 Calories/hr (Calorie = kilogram calorie and calorie = gram calorie) (23.9 BTU/hr or 110.4 W) are added to the thermal burden when the ambient temperature is 90°F (32.2°C) (383). The parameters illustrated in Figure 6, and the values selected for this analysis, are summarized in Table 4.

The design of the thermoelectric heat pump module is based on the material properties for industrial grade bismuth telluride (Bi_2Te_3). The material parameters are summarized in Table 5 (295,299,301,309,316,319,322,325,326, 329,336,343,347,363).

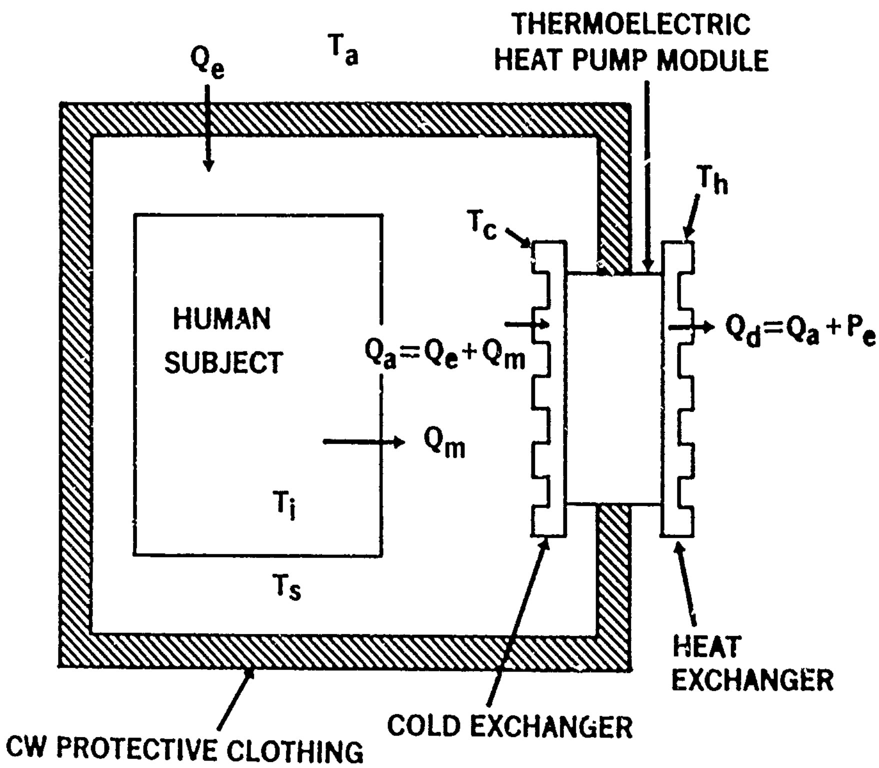


Figure 6. Model of the thermal conditioning problem for an individual dressed in CW protective clothing.

TABLE 3. HUMAN METABOLIC RATES AND THEIR ASSOCIATED AVERAGE HEAT LOADS

Metabolic Rate	Average Heat Load (Q_m) (W)	(BTU/hr)	(Calories/hr)*
Rest	93	20.2	80
Light work	520	112.7	447.4
Moderate work	690	149.6	593.7
Heavy work	1035	224.4	890.5
All-out effort	1850	401.1	1591.8

*Calorie = kilogram calorie

TABLE 4. SUMMARY OF THE VALUES SELECTED FOR THE MODEL IN FIGURE 6

Parameter	Value
Q_a	$Q_e + Q_m$ (see Table 3)
Q_d	$Q_a + P_e$ (to be calculated)
Q_e	95 Calories/hr (23.9 BTU/hr)(110.4 W)
Q_m	(See Table 3)
T_a	90°F (32.2°C)(305.36°K)
T_c	74°F (23.3°C)(296.46°K)
T_h	105°F (40.6°C)(313.76°K)
T_i	98.6°F (37°C)(310.16°K)
T_s	74°F (23.3°C)(296.46°K)

TABLE 5. THERMOELECTRIC MATERIAL PROPERTIES

Parameter	Value
$\alpha_{n\text{-type}}$	$-232\ \mu V \cdot {}^\circ K^{-1}$
$\alpha_{p\text{-type}}$	$228\ \mu V \cdot {}^\circ K^{-1}$
$k_{n\text{-type}}$	$0.016\ W \cdot {}^\circ K^{-1} \cdot cm^{-1}$
$k_{p\text{-type}}$	$0.014\ W \cdot {}^\circ K^{-1} \cdot cm^{-1}$
$\rho_{n\text{-type}}$	$1.11\text{x}10^{-3}$ ohm • cm
$\rho_{p\text{-type}}$	$1.12\text{x}10^{-3}$ ohm • cm
$\ell_{n\text{-type}}$	0.125 in. (0.3175 cm)
$\ell_{p\text{-type}}$	0.125 in. (0.3175 cm)
$A_{n\text{-type}}$	$4.91\text{x}10^{-2}$ in.^{2} (0.3167 cm^2)
$A_{p\text{-type}}$	$4.91\text{x}10^{-2}$ in.^{2} (0.3167 cm^2)

Design for Maximum Coefficient of Performance

Since, in a number of case analyses, several of the results for specific calculations will be used, they will be made next and applied accordingly:

From Equation (3):

$$\alpha = [228 - (-232)]$$

$$\alpha = 4.6\text{x}10^{-4}\ \text{volts} \cdot {}^\circ K^{-1}$$

From Equation (8):

$$k = \left[\frac{(0.014)(0.3167)}{(0.3175)} + \frac{(0.016)(0.3167)}{(0.3175)}\right]$$

$$k = 2.99 \times 10^{-2}\ W \cdot {}^\circ K^{-1} \cdot cm^{-1}$$

From Equation (10):

$$R = \left[\frac{(1.12x10^{-3})(0.3175)}{(0.3167)} + \frac{(1.11x10^{-3})(0.3175)}{(0.3167)}\right]$$

$$R = 2.24 \text{ x } 10^{-3} \text{ ohms}$$

From Equation (19):

$$\Delta T = (313.76 - 296.46)$$

$$\Delta T = 17.3°K$$

From Equation (32):

$$Z = \left\{\frac{(4.6x10^{-4})}{[(1.11x10^{-3})(0.016)]^{1/2} + [(1.12x10^{-3})(0.014)]^{1/2}}\right\}^2$$

$$Z = 3.18x10^{-3}\,°K^{-1}$$

From Equation (35):

$$\overline{T} = 1/2(313.76+296.46)$$

$$\overline{T} = 305.11°K$$

From Equation (34):

$$\omega = [1 + (3.18x10^{-3})(305.11)]^{1/2}$$

$$\omega = 1.404$$

From Equation (36):

$$\Phi_{max} = \left(\frac{296.46}{17.3}\right)\left\{\frac{1.404-\left(\frac{313.76}{296.46}\right)}{1.404+1}\right\}$$

$$\Phi_{max} = 2.46$$

From Equation (33):

$$I = \frac{(4.6\text{x}10^{-4})(17.3)}{(2.24\text{x}10^{-3})(1.404-1)}$$

I = 8.794 amperes

From Equation (37):

$$V = \frac{(4.6\text{x}10^{-4})(17.3)(1.404)}{(1.404-1)}$$

V = 0.028 volts per couple

Finally, from Equation (38):

$$P = \left(\frac{1.404}{2.24\text{x}10^{-3}}\right)\left[\frac{(4.6\text{x}10^{-4})(17.3)}{(1.404-1)}\right]^2$$

P = 0.246 W per couple

For each metabolic rate, a case analysis will be accomplished to determine the number of couples required to dissipate the heat load and the operating power supply voltage. The number of couples required to dissipate a given heat load is expressed as:

$$N = \frac{\text{Net heat to be pumped}}{\text{Heat pumped per couple}} \qquad (46)$$

The operating supply voltage (V_o) is given by:

$$V_o = (\text{Voltage per couple})(\text{Number of couples})$$

or

$$V_o = VN \qquad (47)$$

Case 1: Metabolic rate at rest (Q_m = 93 W)

From Figure 6 and Table 4:

Q_a = 110.4 + 93

Q_a = 203.4 W

From Equation (46):

$$N = \frac{203.4}{0.246}$$

N = 827 couples

From Equation (47):

V_o = (0.028)(827)

V_o = 23.2 volts

Case 2: Metabolic rate for light work (Q_m = 520 W)

From Figure 6 and Table 4:

Q_a = 110.4 + 520

Q_a = 630.4 W

From Equation (46):

$$N = \frac{630.4}{0.246}$$

N = 2563 couples

From Equation (47):

V_o = (0.028)(2563)

V_o = 71.8 volts

Case 3: Metabolic rate for moderate work (Q_m = 690 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 690$$

$$Q_a = 800.4 \text{ W}$$

From Equation (46):

$$N = \frac{800.4}{0.246}$$

$$N = 3254 \text{ couples}$$

From Equation (47):

$$V_o = (0.028)(3254)$$

$$V_o = 91.1 \text{ volts}$$

Case 4: Metabolic rate for heavy work (Q_m = 1035 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 1035$$

$$Q_a = 1145.4 \text{ W}$$

From Equation (46):

$$N = \frac{1145.4}{0.246}$$

$$N = 4657 \text{ couples}$$

From Equation (47):

$$V_o = (0.028)(4657)$$

$$V_o = 130.4 \text{ volts}$$

Case 5: Metabolic rate for all-out effort (Q_m = 1850 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 1850$$

$$Q_a = 1960.4 \text{ W}$$

From Equation (46):

$$N = \frac{1960.4}{0.246}$$

$$N = 7970 \text{ couples}$$

From Equation (47):

$$V_o = (0.028)(7970)$$

$$V_o = 223.2 \text{ volts}$$

Summarized in Table 6 are the important parameters for the maximum coefficient of performance design:

TABLE 6. MAXIMUM COEFFICIENT OF PERFORMANCE DESIGN

	Power Supply Requirements			
Metabolic rate	Current (amperes)	Voltage (volts)	Power (W)	No. of couples
Rest	8.794	23.2	204.1	827
Light work	8.794	71.8	631.4	2563
Moderate work	8.794	91.1	801.1	3254
Heavy work	8.794	130.4	1146.7	4657
All-out effort	8.794	223.2	1962.8	7970

Design for Maximum Heat Pump Capacity

Since, in a number of case analyses, several of the results for specific calculations will be used, they will be made next using applicable values calculated in the previous section:

From Equation (41):

$$I = \frac{(4.6x10^{-4})(296.46)}{(2.24x10^{-3})}$$

$$I = 60.9 \text{ amperes}$$

From Equation (42):

$$V = (4.6x10^{-4})(313.76)$$

$$V = 0.144 \text{ volts per couple}$$

From Equation (43):

$$Q_{c\ max} = [\frac{(4.6x10^{-4})^2(296.46)^2}{(2)(2.24x10^{-3})}] - (2.99x10^{-2})(17.3)$$

$$Q_{c\ max} = 4.15 \text{ watts per couple}$$

<u>Case 1</u>: Metabolic rate at rest (Q_m = 93 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 93$$

$$Q_a = 203.4 \text{ W}$$

From Equation (46):

$$N = \frac{203.4}{4.15}$$

$$N = 50 \text{ couples}$$

From Equation (47):

$$V_o = (0.144)(50)$$

$$V_o = 7.2 \text{ volts}$$

<u>Case 2</u>: Metabolic rate for light work (Q_m = 520 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 520$$

$$Q_a = 630.4 \text{ W}$$

From Equation (46):

$$N = \frac{630.4}{4.15}$$

$$N = 152 \text{ couples}$$

From Equation (47):

$$V_o = (0.144)(152)$$

$$V_o = 21.9 \text{ volts}$$

<u>Case 3</u>: Metabolic rate for moderate work (Q_m = 690 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 690$$

$$Q_a = 800.4 \text{ W}$$

From Equation (46):

$$N = \frac{800.4}{4.15}$$

$$N = 193 \text{ couples}$$

From Equation (47):

$$V_o = (0.144)(193)$$

$$V_o = 27.8 \text{ volts}$$

Case 4: Metabolic rate for heavy work (Q_m = 1035 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 1035$$

$$Q_a = 1145.4 \text{ W}$$

From Equation (46):

$$N = \frac{1145.4}{4.15}$$

$$N = 276 \text{ couples}$$

From Equation (47):

$$V_o = (0.144)(276)$$

$$V_o = 39.8 \text{ volts}$$

Case 5: Metabolic rate for all-out effort (Q_m = 1850 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 1850$$

$$Q_a = 1960.4 \text{ W}$$

From Equation (46):

$$N = \frac{1960.4}{4.15}$$

$$N = 473 \text{ couples}$$

From Equation (47):

$$V_O = (0.144)(473)$$

$$V_O = 68.1 \text{ volts}$$

Summarized in Table 7 are the important parameters for the maximum heat pump capacity design:

TABLE 7. MAXIMUM HEAT PUMP CAPACITY DESIGN

Metabolic rate	Power Supply Requirements Current (amperes)	Voltage (volts)	Power (W)	No. of couples
Rest	60.9	7.2	438.5	50
Light work	60.9	21.9	1333.7	152
Moderate work	60.9	27.8	1693.1	193
Heavy work	60.9	39.8	2423.8	276
All-out effort	60.9	68.1	4147.3	473

Discussed in the next section are the meaning of these calculations, and the problems one might encounter trying to implement them with hardware.

IMPLEMENTING A THERMOELECTRIC HEAT PUMP DESIGN

Comments on Design Calculations

The primary components of a thermoelectric cooling system are: the thermoelectric module design; the transfer of thermal energy between a thermoelectric surface and the ambient medium surrounding it; and the source of electrical energy to power the thermoelectric modules. The authors will use the results of the "moderate metabolic rate" condition to complete the analysis of a thermoelectric cooling system design. (This decision was made because the "moderate metabolic rate" represents an "average" workload for the problem at hand.)

Thermoelectric Module Design

A thermoelectric module is an assembly of several thermoelectric semiconductor elements (couples). By definition, a thermoelectric module is the smallest assembly of elements that can be physically interchanged as a unit in thermoelectric system (3,8-16,384). The number of elements in a module, or its heat pumping capacity, are not specified in the module definition.

The two basic types of thermoelectric modules are: electrically isolated, and electrically insulated (8-16,54,234).

The electrically isolated module is known as a direct transfer device. This module design divides the heat exchanger into segments, and each segment transfers heat from one side to its other side. A cross-sectional view of this design is shown in Figure 7. This design is used primarily in large air-conditioning applications.

The electrically insulated variant is the most common thermoelectric module design. In this type of module, a layer of electrical insulation is sandwiched between the thermoelectric elements and the heat exchanger base. Shown in Figure 8 is a cross-sectional view of a typical electrically insulated module. Since the layer of electrical insulation is directly in the heat path, this insulation must be a good thermal conductor; consequently, the range of materials is strictly limited (e.g., Mylar, glass, aluminum oxide, epoxy resin, mica, and silicon grease). The geometry (thin, flat, large planar surface area) makes this design a better choice for regulating the thermal burden imposed by CW protective clothing.

A typical commercially available module contains 44 of the elements (or 22 couples), is 1.5 in. by 1.5 in. by 0.25 in. thick (3.81 cm by 3.81 cm by 0.64 cm thick), weighs approximately 25 grams, and costs approximately $30/module (254-257). Summarized in Table 8 are the important parameters associated with the size, volume, and weight of the thermoelectric module for the metabolic rate requirements of moderate work.

As indicated in Table 8, the maximum heat pump capacity parameters would be very compatible with integrating the thermoelectric cooling system on the ground troop's back. The maximum coefficient of performance parameters is not as desirable. The surface area requirement approaches, if not exceeds, the surface area available on an average male's back; the weight of the thermoelectric modules exceeds 8 lb; and the cost is not realistic. Could optimization of the design by computer techniques produce a more cost effective and physically compatible (with the individual--particularly surface area and weight) design? The answer is probably "Yes."

Thermoelectric Module Heat Transfer

For normal operation of a thermoelectric cooling device, it is necessary to provide efficient heat coupling between the thermoelectric module and the area or volume to be thermally regulated on one hand, and with the heat transfer system on the other. The purpose of a heat transfer system is to dissipate heat from the hot junction of a thermoelectric module. The four basic types of heat transfer systems (385-406) are:

a. air on both sides,
b. air on cold side and fluid on hot side,
c. air on hot side and fluid on cold side, and
d. fluid on both sides.

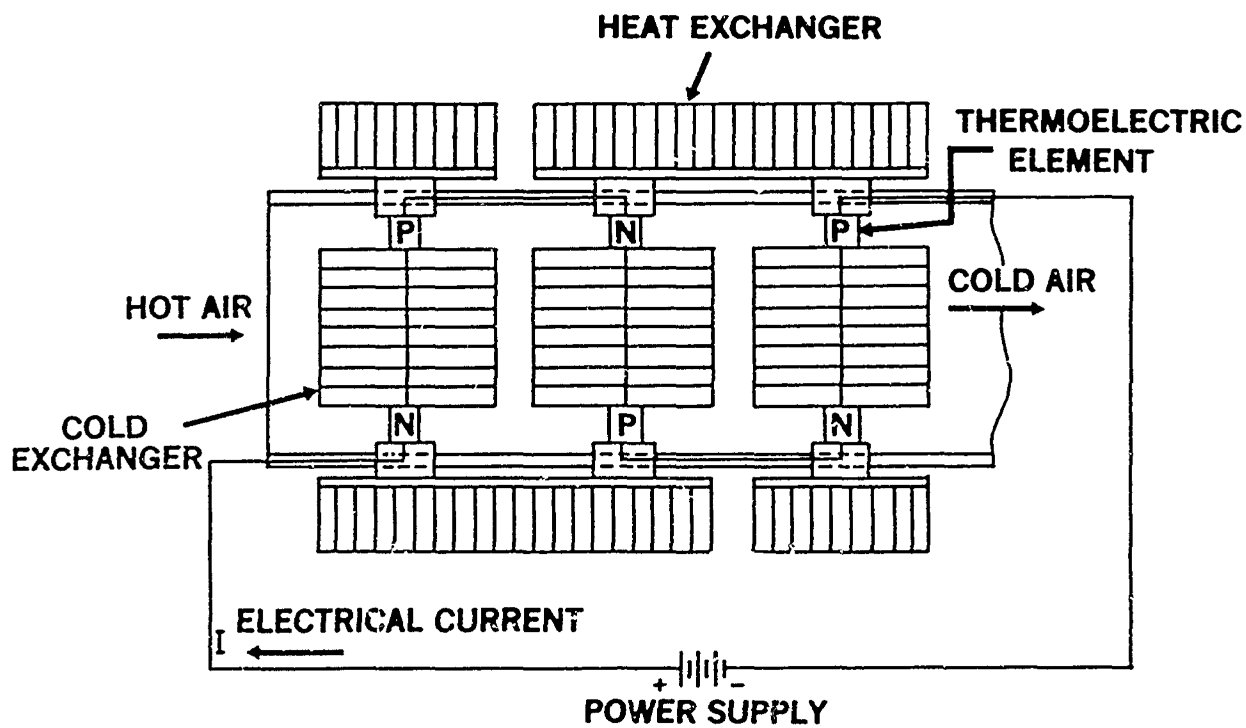


Figure 7. Electrically isolated thermoelectric module (cross-sectional view).

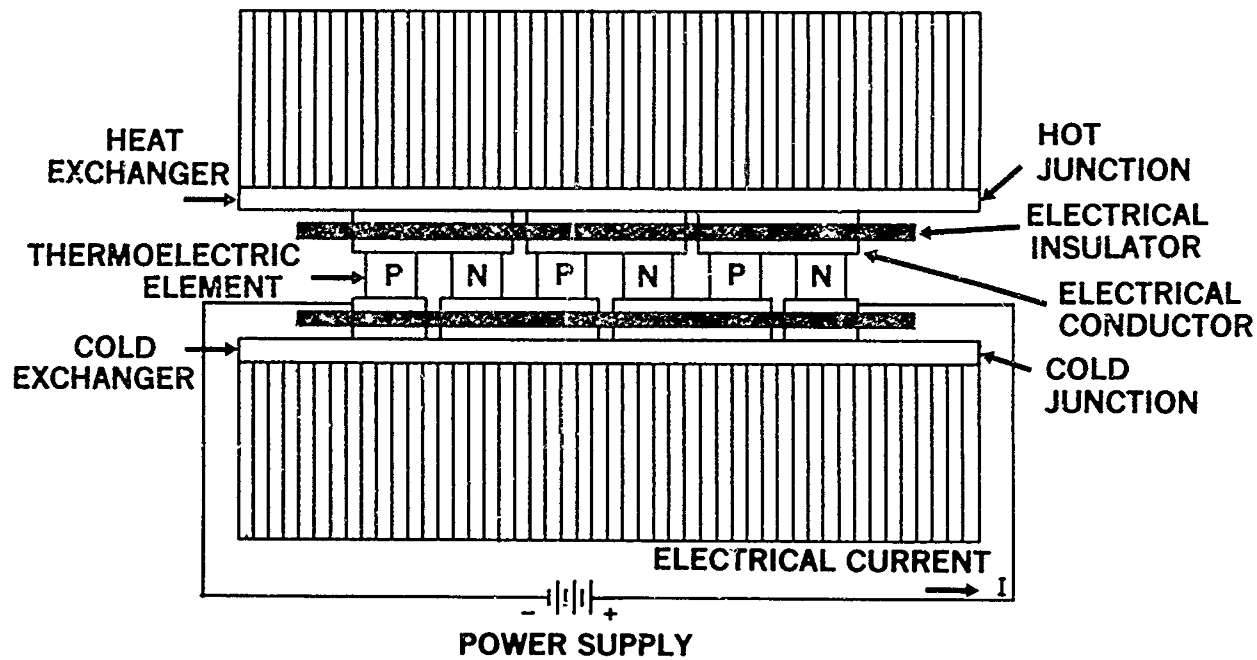


Figure 8. Electrically insulated thermoelectric module (cross-sectional view).

TABLE 8. THERMOELECTRIC MODULE PHYSICAL CHARACTERISTICS

Design	No. of modules	Surface area of modules ($in.^2/cm^2$)	Volumetric module displacement ($in.^3/cm^3$)	Weight of modules (grams)	Cost ($)
Maximum coefficient of performance	148	333/2148.4	83.25/1364.2	3700	$4400
Maximum heat pump capacity	9	20.25/130.7	5.1/83	225	$270

Each of these heat transfer systems has been considered for this cooling system design, and their respective advantages and disadvantages are summarized in Table 9 (386,391,392,397,398,401,402,404).

The "air on both sides" heat transfer system is the simplest technology. Since simplicity is of prime importance in the problem at hand, the author selected this system for more detailed analysis.

The "air on both sides" heat transfer process is a convective phenomenon. From Figure 6 and Equations (12), (14), and (16), the total heat flow (Q_h) at the hot junction must be dissipated from the thermoelectric cooling system for efficient operation. The convective heat transfer process (3,8-16,385, 387-389,403) is governed by the following equation:

$$Q_d = \eta \beta A b (T_h - T_a) \tag{48}$$

where η is the fin efficiency factor that accounts for the fact that the fins are not isothermal at their base temperature (T_h); β is the heat exchanger fin factor (equal to the ratio of total fin and plate area to the base plate area); A is the base plate area; b is the heat-transfer coefficient for free or forced convection; and T_a is the ambient temperature.

Representative ranges of values for these parameters (8-16,387-389) are:

a. $0.7 < \eta < 1.0$	
b. $1.0 < \beta < 20.0$	
c. A will be calculated	ft^2
d. $0.5 < b < 1.0$	$BTU \cdot hr^{-1} \cdot ft^2 \cdot °F$ (free convection)
e. $2.0 < b < 5.0$	$BTU \cdot hr^{-1} \cdot ft^2 \cdot °F$ (forced convection)
f. $10.0 < (T_h - T_a) < 30.0$	°F

For the moderate metabolic rate considered in this analysis, the value of Q_d must be calculated. From Figure 6, Table 6, Table 7, and the values of Q_a calculated in the case analyses--the value of Q_d for maximizing the coefficient of performance is approximately 1600 W. Similarly, the value of Q_d for maximizing the heat pump capacity is approximately 2500 W.

TABLE 9. EVALUATION OF HEAT TRANSFER SYSTEMS

Type of system	Advantages	Disadvantages
Air on both sides	Lightest possible weight Simple design Easy to maintain	Complex air baffling Least efficient Uneven temperature distributions on exchangers Requires large surface area Hot side thermoelectric modules may overheat
Air on cold side and fluid on hot side	Moderate weight Hot side exchanger surface area can be reduced	Uneven temperature distribution on cold side Maintenance problems increased Noise level increases (pumps) Potential fluid leaks Requires more electrical power (pumps)
Air on hot side and fluid on cold side	Moderate weight Cooler hot exchanger Uniform temperature distribution on cold side	Uneven temperature distribution on hot side Maintenance problems increased Noise level increases (pumps) Potential fluid leaks Requires more electrical power (pumps)
Fluid on both sides	Isolation of thermoelectric module components from environmental contaminants Uniform temperature distribution on hot and cold sides	Most expensive Highest noise levels Highest weight Highest maintenance burden Potential for leaks Highest consumption of additional electrical power (pumps)

Summarized in Table 10 is the heat transfer surface area requirement for the moderate metabolic rate, for free and forced convection, and for selection of the optimum values for the parameters in Equation (48).

As can be observed from Table 10, the required surface areas for the heat transfer sinks are very large, and the associated weight would prohibit implementation with a human subject. Computer optimization of the thermoelectric module design would not resolve this problem. Perhaps one of the liquid transfer schemes would be of benefit, but then such objectives as simplicity and low cost would be compromised.

Power Supply

One of the primary components of a thermoelectric cooling system is the power supply. The selection of a power supply affects such factors in a thermoelectric module as configuration and design, duration of continuous operation, cost, and mass.

The current power supply technologies available for the production of electrical energy include chemical fuels, solar, radioisotopes, and storage batteries (407-416). The most suitable power supply technology for a portable thermoelectric cooling system is the storage battery.

Fundamentally, storage batteries are classified as "primary" if they cannot be recharged or are intended for a single discharge, and as "secondary" if they can be recharged or are intended to be charged or discharged (cycled a number of times). For the thermoelectric cooling system being analyzed, the secondary storage battery offers the most flexibility and long-term economics.

The important characteristics of the four major types of commercially available secondary storage batteries are summarized in Table 11 (417-430).

According to the characteristics in Table 11, the most suitable power supply for a portable thermoelectric cooling system is the silver-zinc secondary storage battery. This battery offers the most with respect to voltage, current delivery capability, and energy density.

Continuing with the design analysis, Table 12 was constructed using the optimum values for the silver-zinc battery and the power supply data in Tables 6 and 7 for the "moderate work" metabolic rate (417-430).

As shown in Table 12, the number of cells, their weight, and displacement are excessive relative to the number of hours they can be expected to perform at the rated load. Computer optimization of the thermoelectric cooling system design will not resolve this problem.

CONCLUSION

The theory, applications, and analysis of the problem of cooling a ground troop dressed in CW protective clothing have been addressed. The analysis has shown that the current thermoelectric cooling technology will not practically

TABLE 10. HEAT TRANSFER THERMAL SINK SURFACE AREA REQUIREMENTS

Design	Heat to be dissipated (W/BTU·hr^{-1})	n	β	Free convection (b)	Forced convection (b)	$(T_h - T_a)$ (°F)
Maximum coefficient of performance	1600/5461	1	20	1	5	15
Maximum heat pump capacity	2500/8532	1	20	1	5	15

TABLE 11. CHARACTERISTICS OF COMMERCIALLY IMPORTANT SECONDARY STORAGE BATTERIES

Characteristic	Gelled-electrolyte (lead acid)	Nickel-cadmium	Silver-cadmium	Silver-zinc
Voltage per cell	2	1.2	1.1	1.5
Capability	30mAh-25Ah	20mAh-10Ah	100mAh-50Ah	50mAh-60Ah
Energy density:				
W·hr/lb	8-10	12-6	22-34	40-50
W·hr/in.^{3}	1.1	1.3-1.7	1.5-2.7	2.5-3.2
Impedance	low	low	very low	very low
Discharge curve	sloping downward	flat	flat	flat
Temperature range (°F):				
Storage	-40 to 100	-40 to 140	-85 to 165	-85 to 165
Discharge	-76 to 140	-40 to 140	-10 to 165	-10 to 165
Charge	32 to 113	32 to 113	32 to 115	32 to 115
Cycle life (deep cycles)	1000	1500	200	50
Relative cost (Rated on a scale of 4 for maximum)	1	2	4	3

TABLE 12. POWER SUPPLY REQUIREMENTS

Design	Current (amperes)	Voltage (volts)	No. of cells	Weight (lb)	Displacement ($in.^3$)	Hours of use at rated load
Maximum coefficient of performance	8.794	91.1	61	109	1703	6.8
Maximum heat pump capacity	60.9	27.8	19	30	476	0.9

or efficiently support the thermal regulation requirements for a human dressed in the CW protective clothing ensemble (for the temperature and thermal loads considered). However, before thermoelectric cooling is totally discarded, one final question should now be considered: If only a portion of the total thermal burden is removed, does thermoelectric cooling become more attractive and realistic? That is, if a thermoelectric cooling system is designed to be compatible with an individual from a physical viewpoint (mass, volumetric displacement, etc.), provided that the design will dissipate X watts, will the performance and length of time that an individual can work in the ensemble be marginally improved?

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

A	surface area
α	Seebeck coefficient
Ag	silver
Ah	ampere-hours
As	arsenic
Ba	barium
Bi	bismuth
b	heat transfer coefficient
β	heat exchanger fin factor
BTU	British thermal unit
Calorie	kilogram-calorie
calorie	gram-calorie
Ce	cerium
Cu	copper
°C	degrees Centigrade
cm	centimeter
cm^2	centimeter squared
cm^3	centimeter cubed
CW	chemical warfare
δ	electrical conductivity
$\frac{df(x)}{dx}$	first derivative [of a function f(x)] with respect to x
ΔT	temperature difference
ΔV	voltage difference
E_g	band-gap energy of a semiconductor
n	efficiency
°F	degrees Fahrenheit
ft^2	foot squared
g	gram
Ge	germanium
hr	hour
I	electrical current
In	indium
in.	inch

$in.^2$	inch squared
$in.^3$	inch cubed
k	thermal conductivity
°K	degrees Kelvin
KR	product of net thermal conductivity and net electrical conductivity
ℓ	length
m	substitution variable used to simplify a complex mathematical expression
m	meter
m^2	meter squared
m^3	meter cubed
mAh	millampere-hours
MITAS	Martin Marietta thermal analysis computer program
Mn	manganese
μV	microvolt
N	number of thermoelectric couples
ν	shape ratio variable (area to length)
N_c	free charge carrier density
n-type	semiconductor with an excess electron concentration
O	oxygen
ω	substitution variable used to simplify a complex mathematical expression
ohm	unit of electrical resistance
P	electrical power
P	phosphorous
Φ	thermoelectric coefficient of performance

Pb	lead
P_e	net Joule heat of a thermoelectric cooling system
p-type	semiconductor with an excess hole concentration
Q_a	heat to be absorbed by the cold junction of a thermoelectric cooling system
Q_c	heat flow into a thermoelectric cold junction
Q_d	heat to be dissipated by a thermoelectric cooling system
Q_e	environmental heat leakage absorbed by a subject dressed in CW protective clothing
Q_F	Fourier heat
Q_h	heat flow from a thermoelectric hot junction
Q_J	Joule heat
Q_m	metabolic heat
Q_P	Peltier heat
Q_T	Thomson heat
R	net electrical resistance
ρ	resistivity
S	sulfur
Sb	antimony
Se	selenium
Si	silicon
T	absolute temperature
τ	Thomson coefficient
(T)	functional temperature dependence
$\overline{T}$	average absolute temperature
T_a	temperature of the ambient air external to a CW protective ensemble

T_c	temperature of a thermoelectric cold junction
Te	tellurium
T_h	temperature of a thermoelectric hot junction
T_i	human temperature (oral)
T_s	temperature of the air inside a CW protective ensemble
V	voltage
V_o	operating power supply voltage
W	watts
x	position
Z	thermoelectric figure of merit
Zn	zinc